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Title: Degradation mechanism of Ni-based superalloy under extreme irradiation environments

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# Degradation mechanism of Ni-based superalloy under extreme irradiation environments

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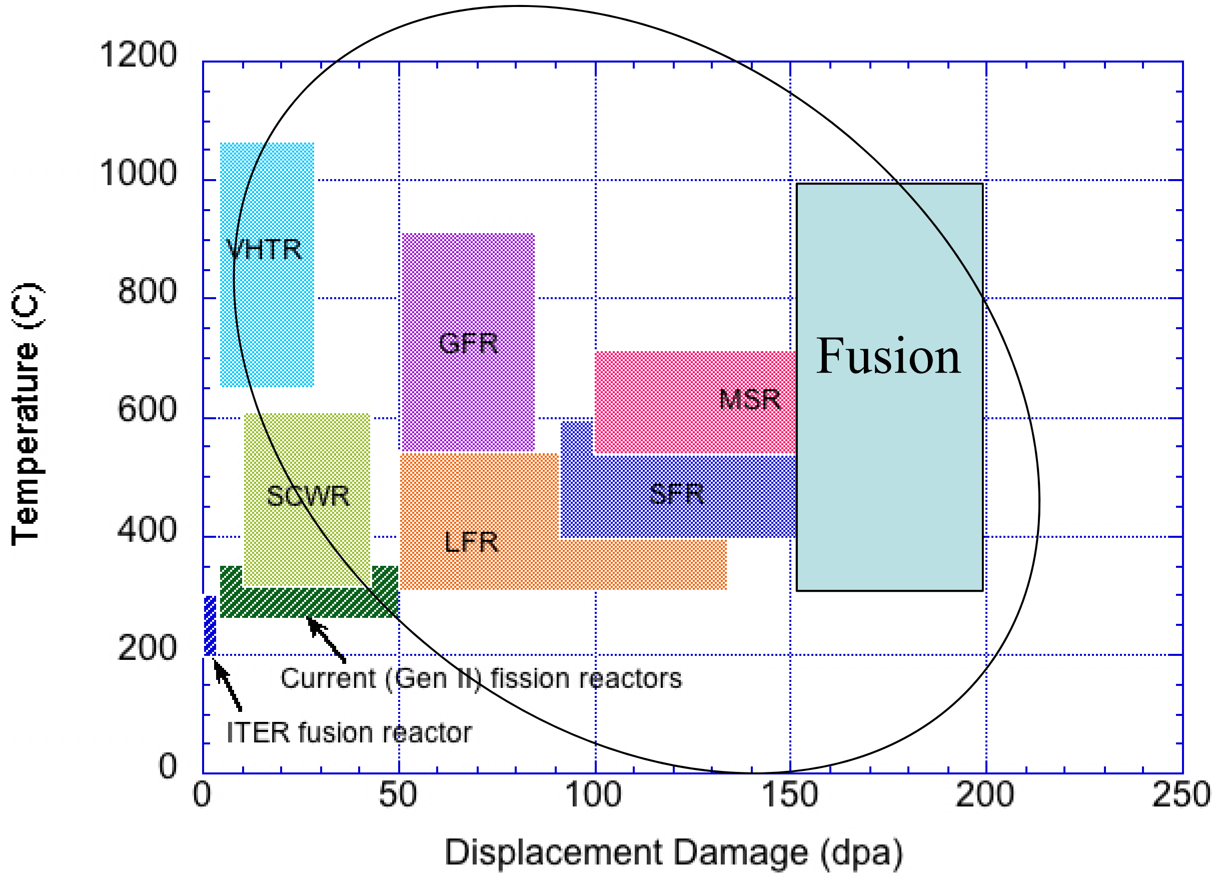
# Outline

- Background/Motivation
- Ni-based superalloy Rene N4 under irradiation
  (C. Sun et al., Acta Materialia, 95(2015):357-365 )
- Conclusions

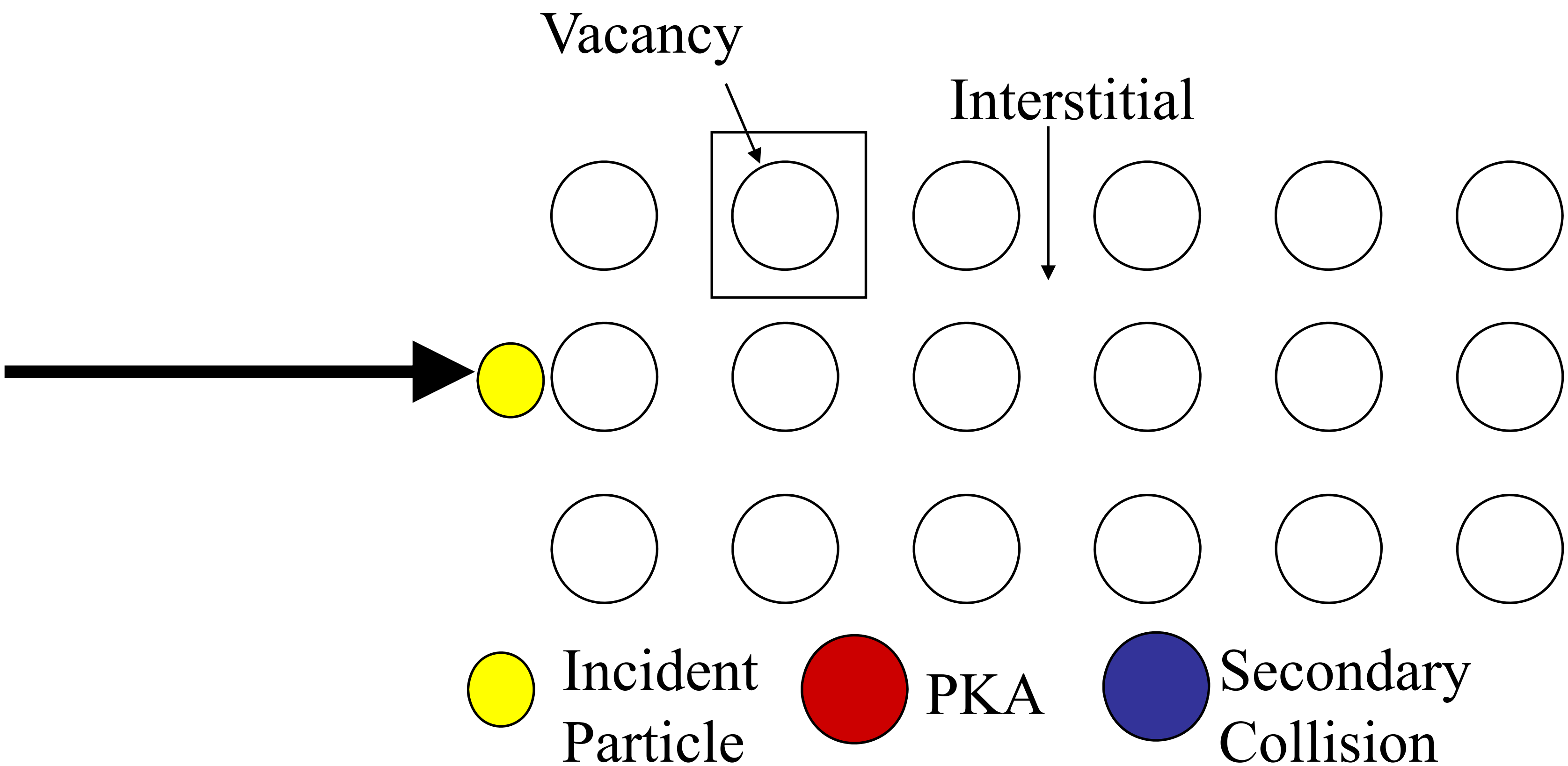
# Materials challenges for Gen IV reactors

*S. J. Zinkle, et al., Mater. Today, 2009*




*How to design irradiation tolerant materials?*

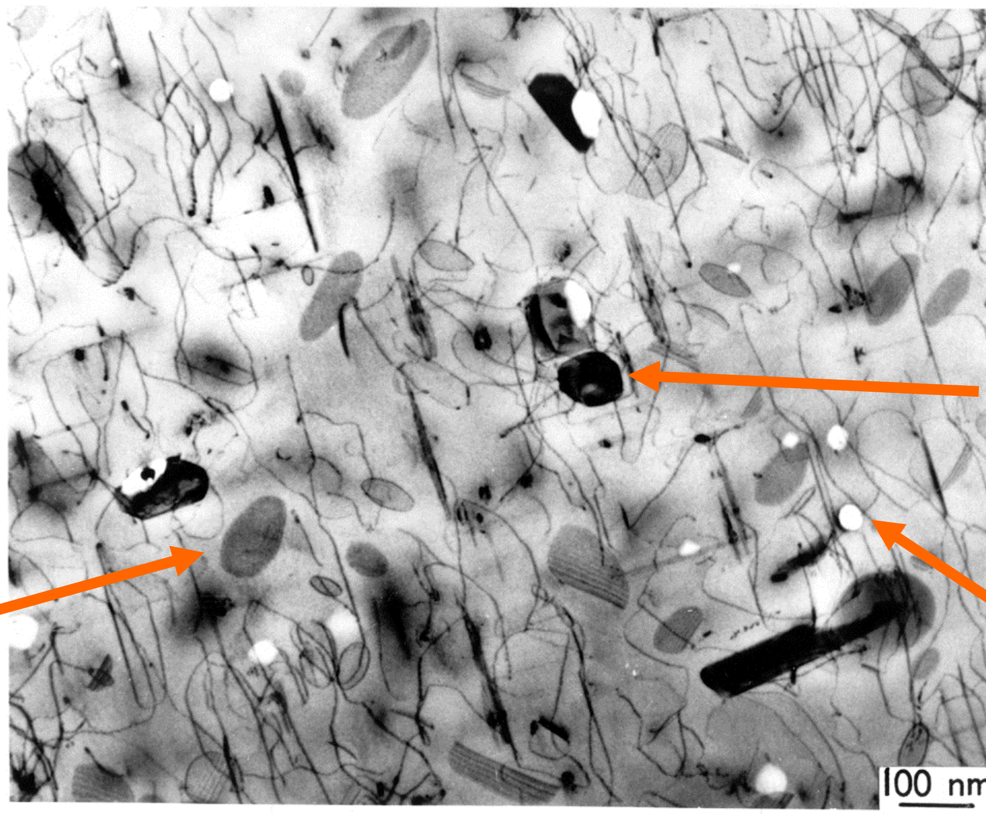
# Radiation damage in metals



# Classic microstructure in neutron irradiated metals

*J. O. Stiegler, 1974*

Dislocation loops




Precipitates

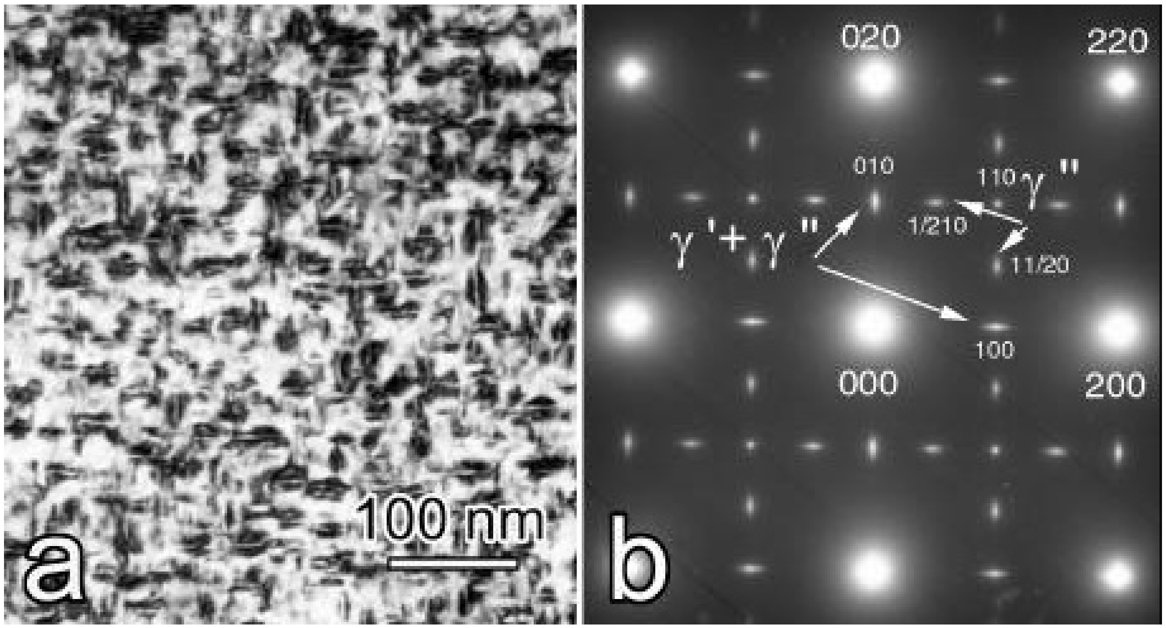
Voids

SA 316 irradiated in EBR-II to $1.9 \times 10^{26}$ n/m$^2$ at 580 °C

# Ni-based superalloys

*B. H Sencer, et al. J. Nucl. Mater., 2001*

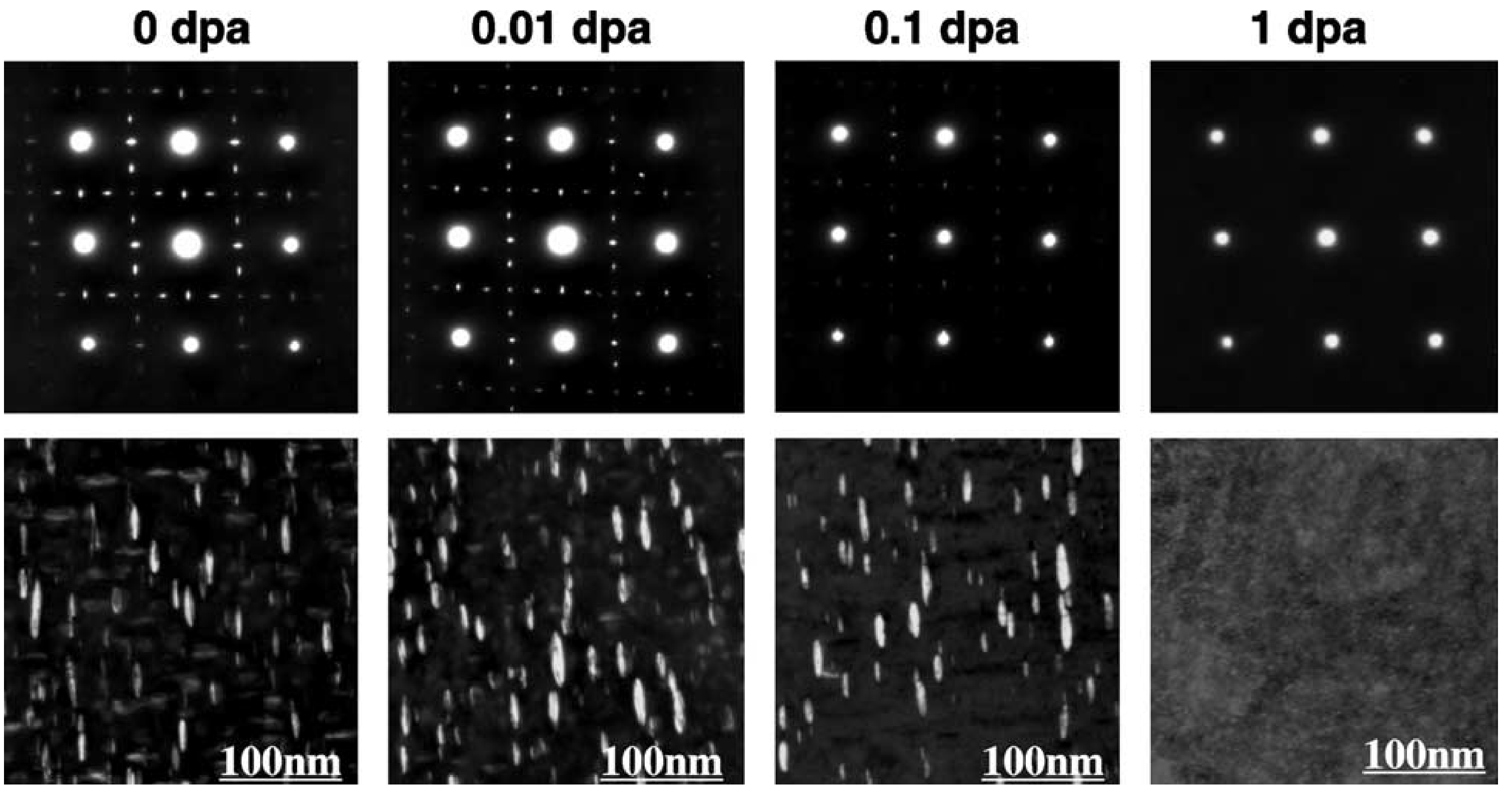
**Inconel 718**




γ (Ni-Fe-Cr), γ'($Ni_3$Al,Ti), γ''($Ni_3$Nb)

# Phase instability under irradiation

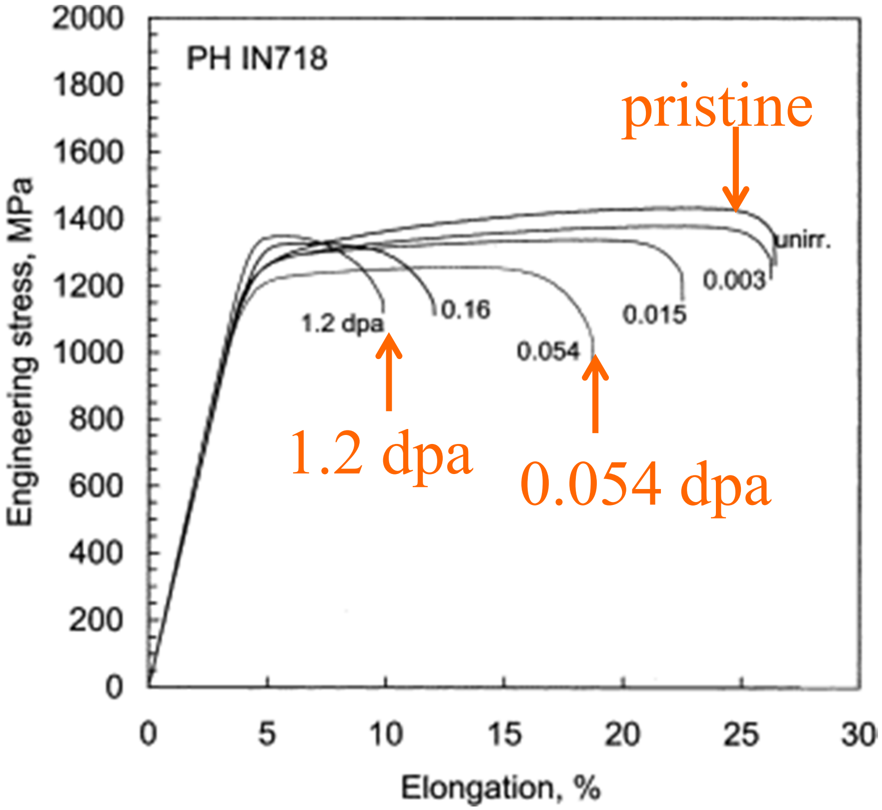
*N. Hashimoto, et al. J. Nucl. Mater., 2003*




Fe ion irradiation/ In 718/ 200°C.

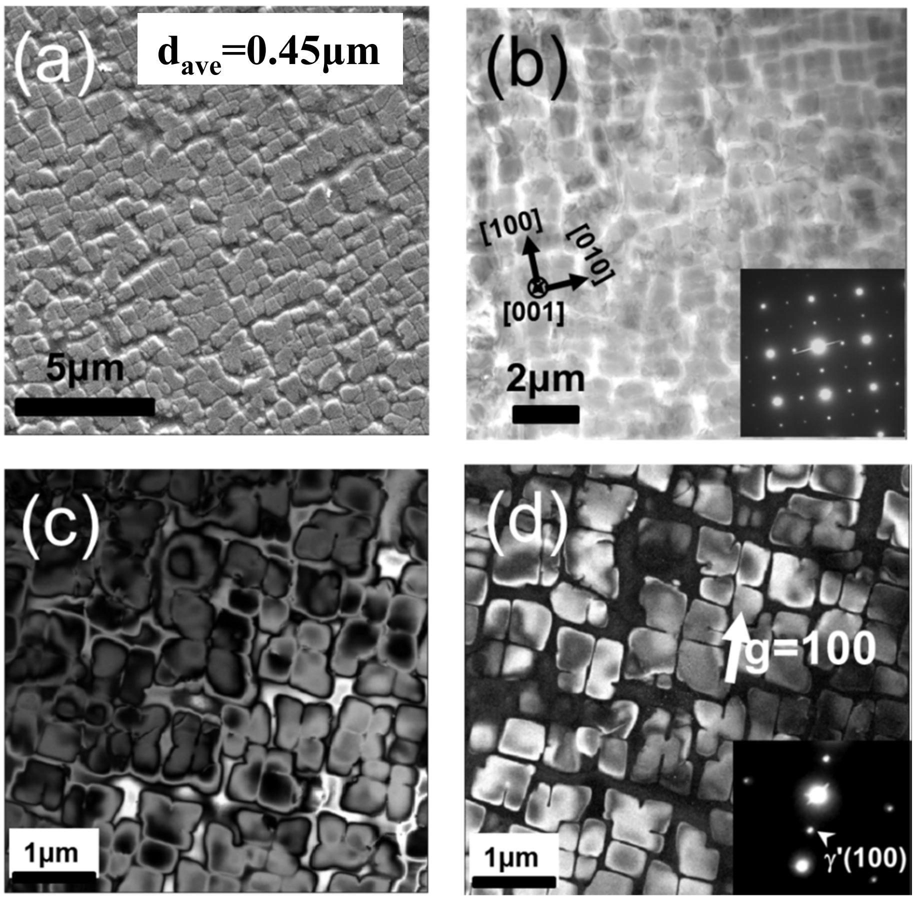
# Mechanical properties under irradiation

*T. S. Byun, et al. J. Nucl. Mater., 2003*




PH In718/ neutron radiation/60-100˚C

# Microstructure of pristine Rene N4




Chemical composition (wt.%)

| | |
|---|---|
| Cr | 9.8 |
| Co | 7.5 |
| Ti | 3.5 |
| Al | 4.2 |
| Mo | 1.5 |
| W | 6.0 |
| Ta | 4.8 |
| Nb | 0.5 |
| Hf | 0.15 |
| Ni | Bal. |

- **Cuboidal $L1_2$ structured γ′ precipitates.**

# Irradiation experiments

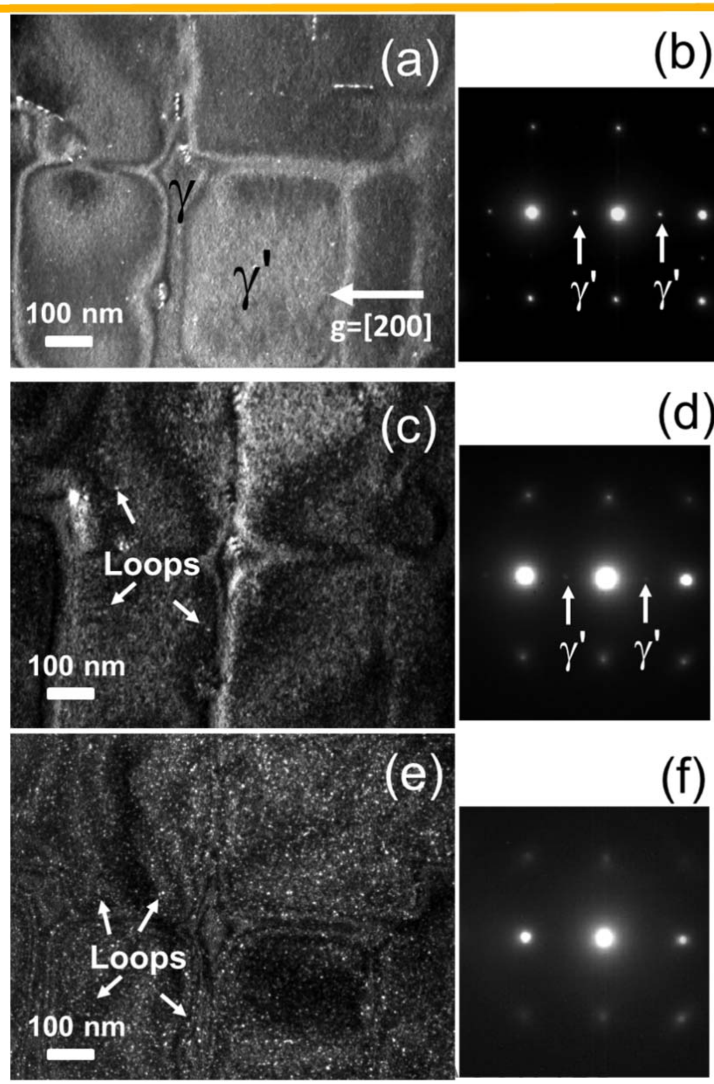
*In situ* Kr ion irradiation
(0-0.3 dpa)


Source: Kr ions
Energy: 1 MeV
Temperature: 30˚C
Fluence: $1\times10^{14}$ /cm$^2$
Model: Non-rastering

*Ex situ* Ni ion irradiation
(0.75, 18, 75dpa)

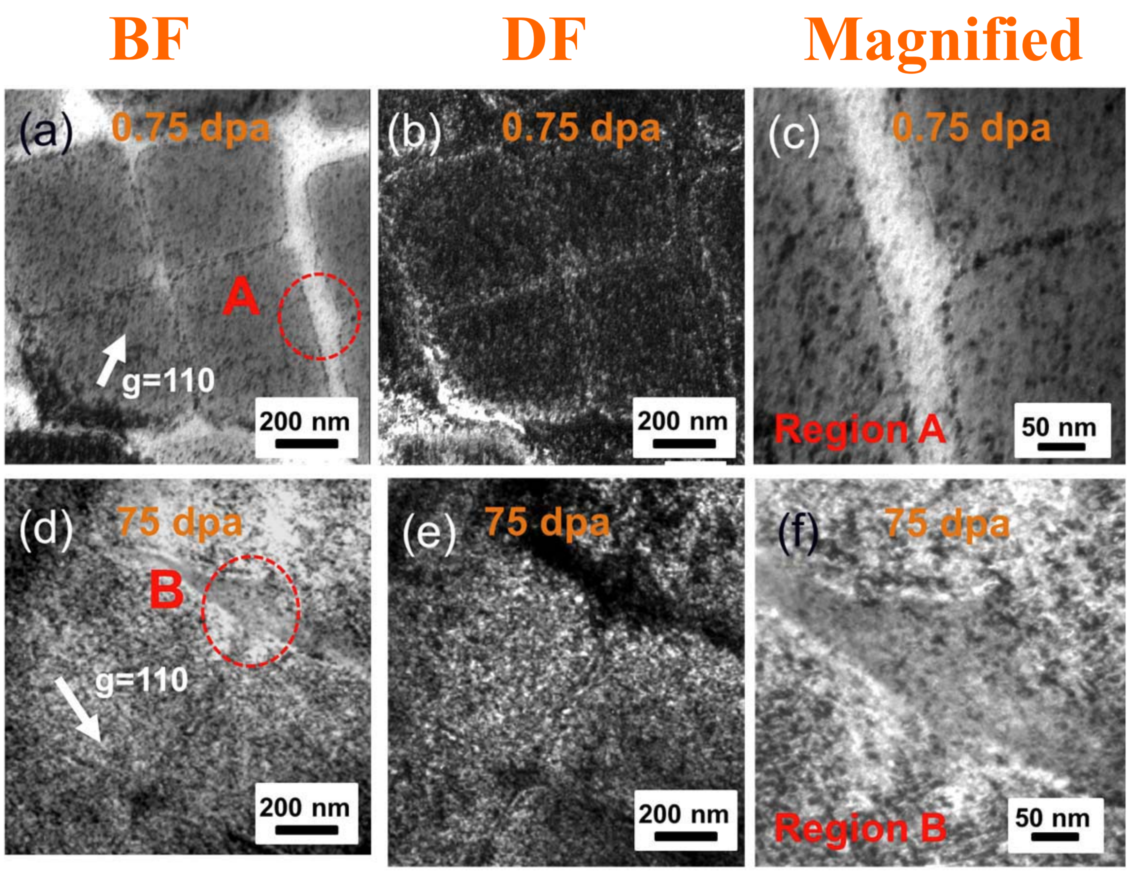
Source: Ni ions
Energy: 3 MeV
Temperature: 20-37˚C
Fluence: $1 \times 10^{17}$ /cm$^2$
Model: Non-rastering

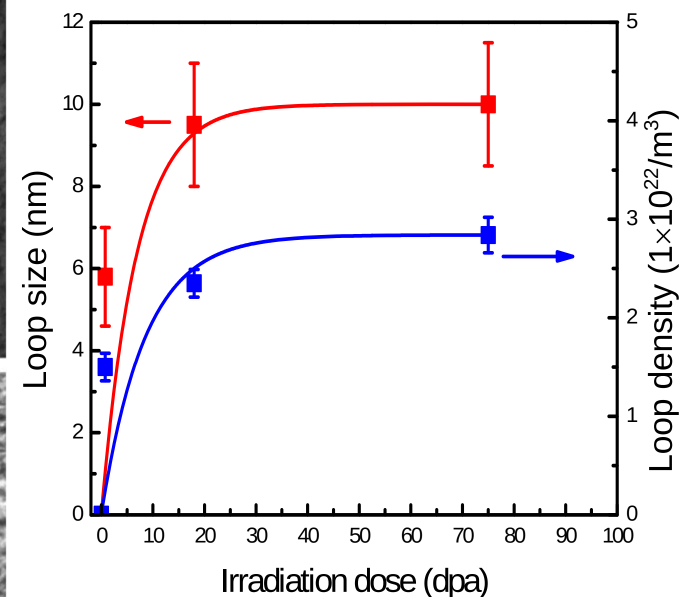
# *In situ* Kr ion irradiation at low doses




- **Dislocation loops are formed.**
- **Complete disorder at 0.3 dpa.**

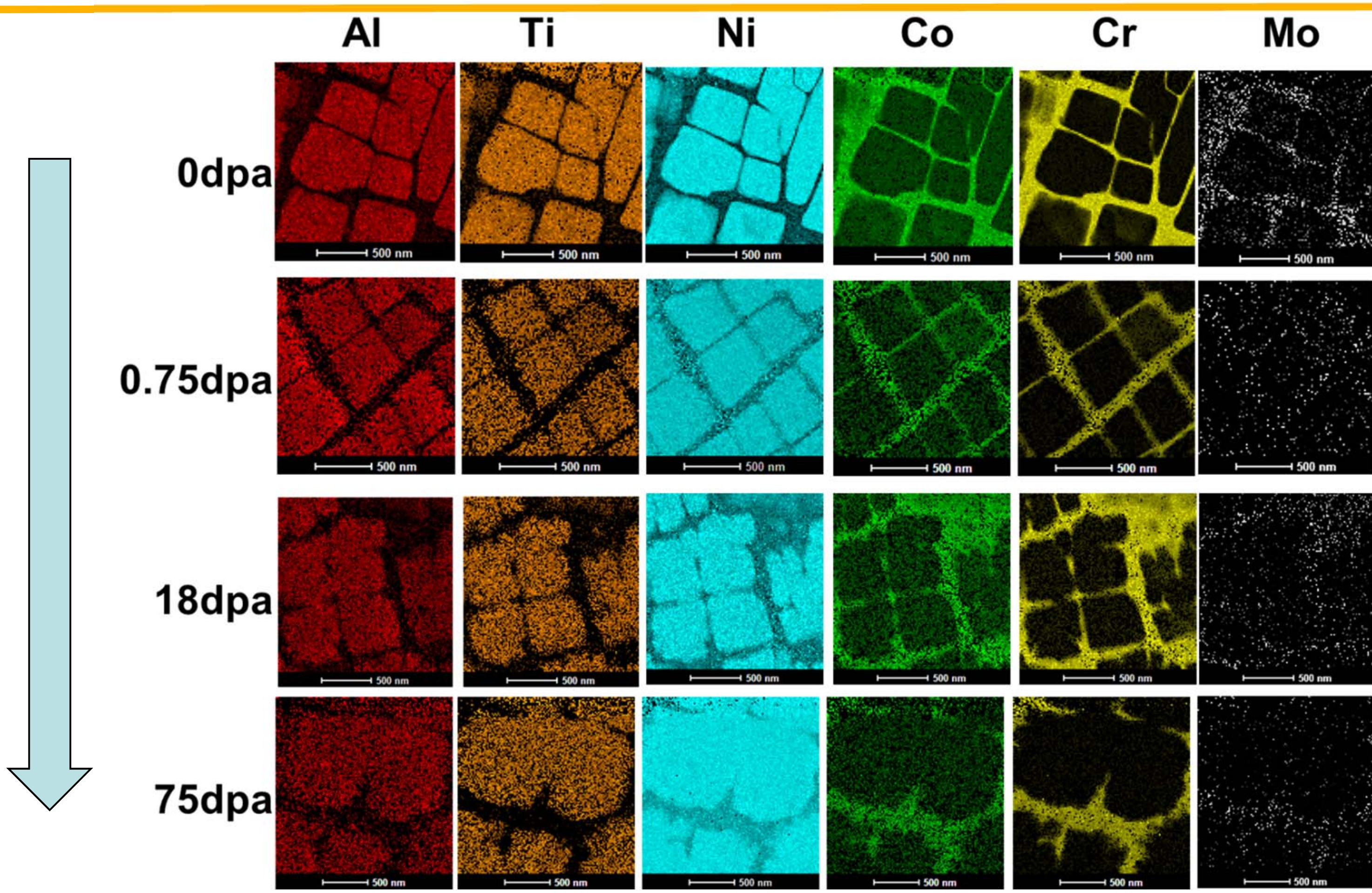
# *Ex situ* Ni ion irradiation to high doses



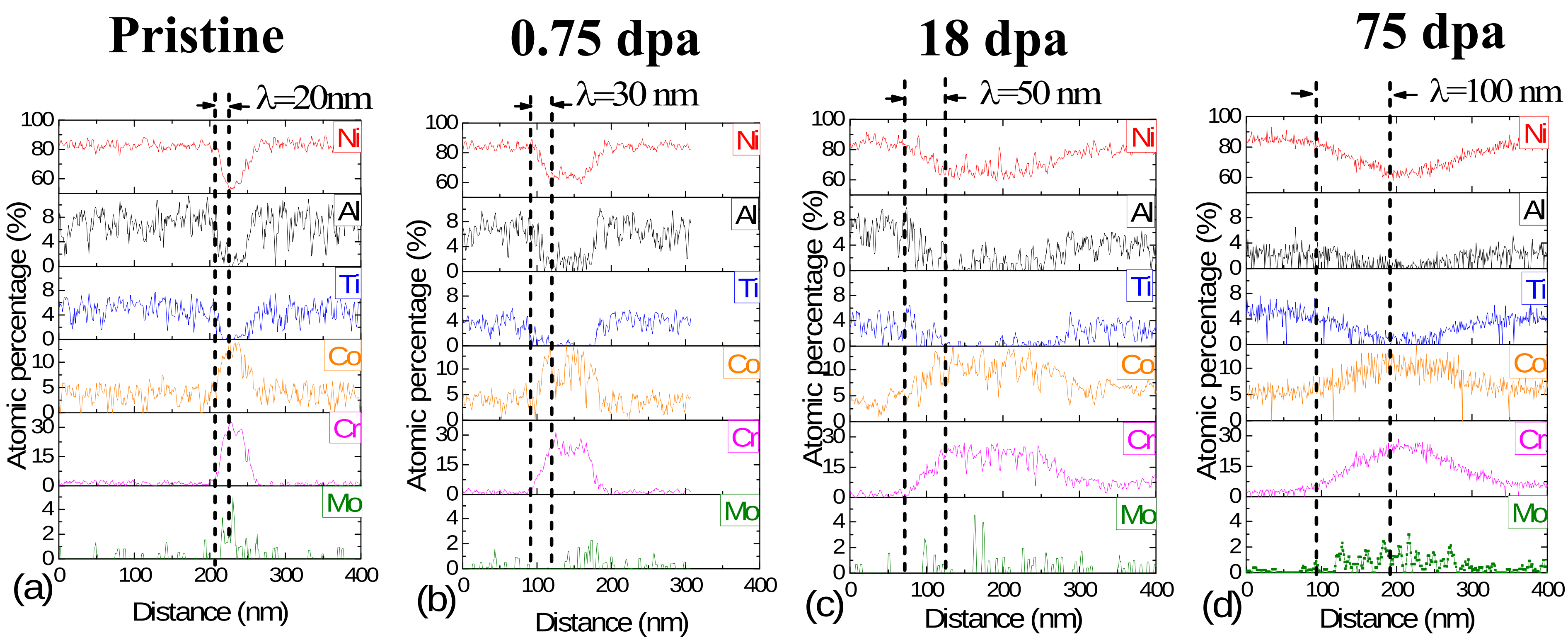

- **Density and size of the dislocation loop are saturated at 18 dpa.**

# Chemical intermixing under irradiation




- **Chemical intermixing-induced coalescence of cuboids.**

# Chemical intermixing under irradiation



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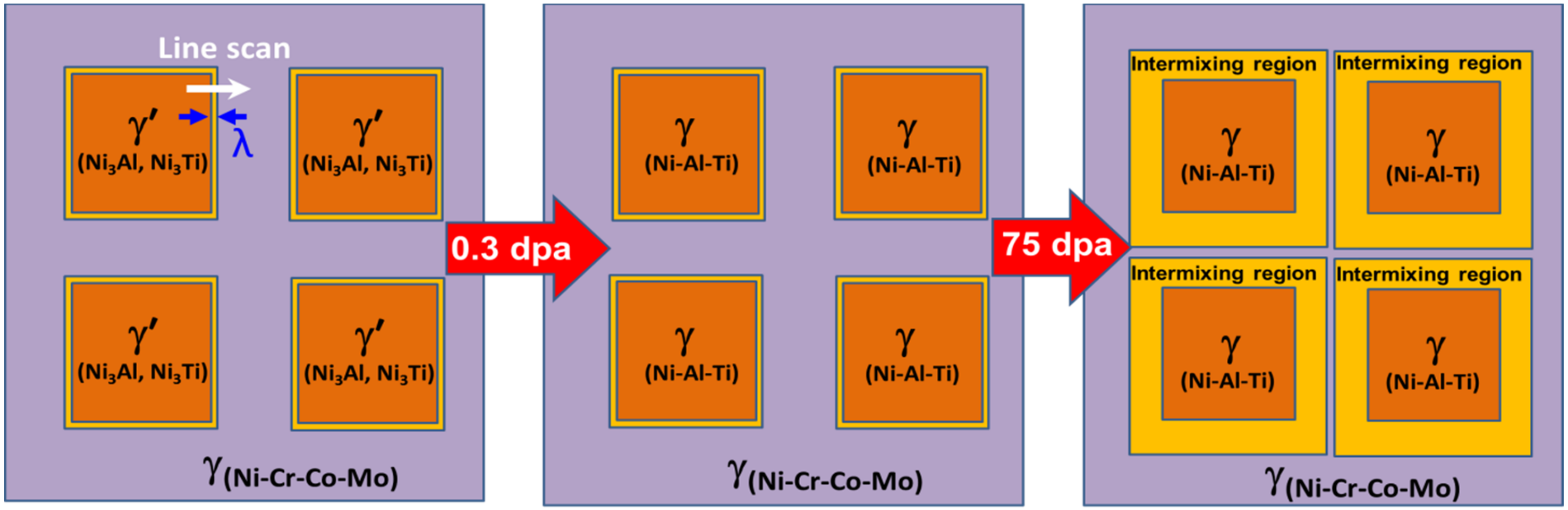
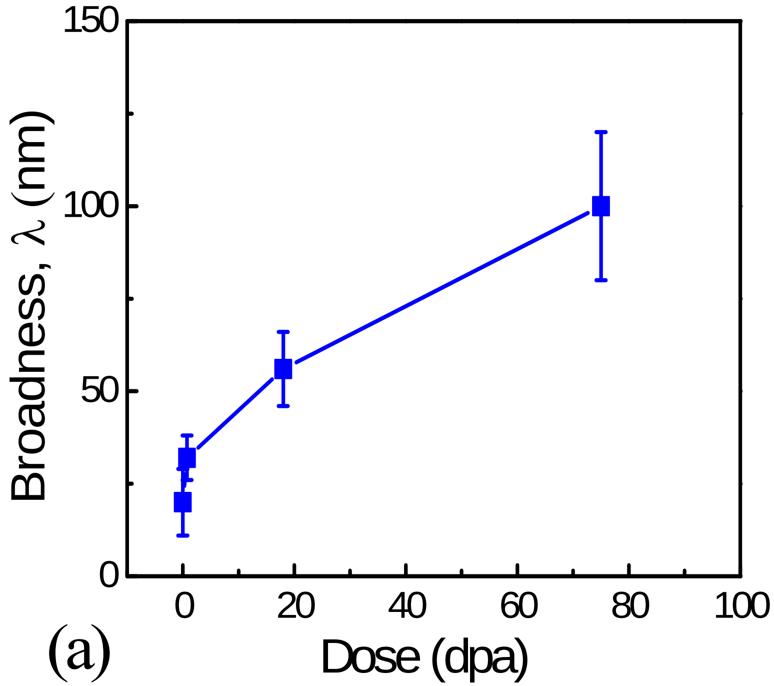
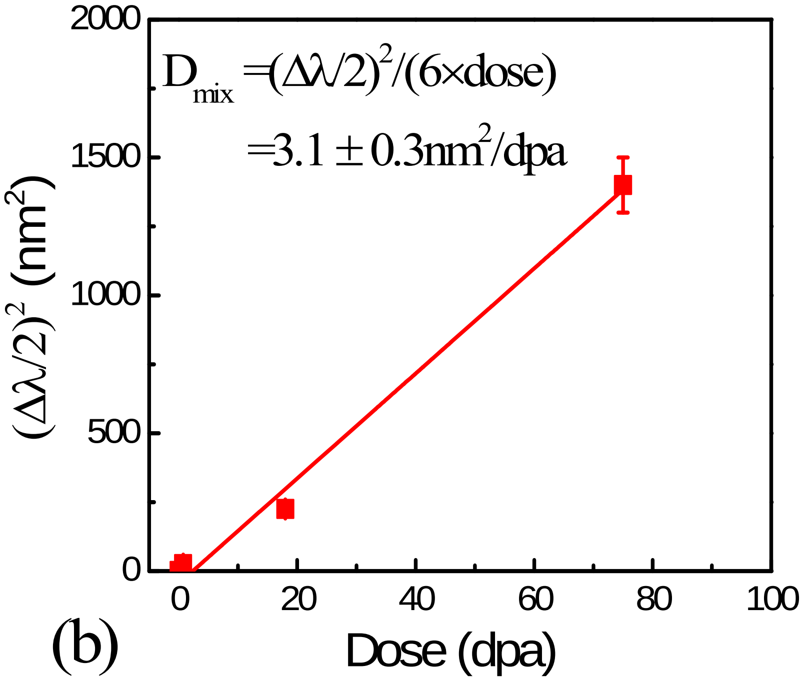


# Chemical intermixing under irradiation




(a)




(b)

# Mixing efficiency (*k*)

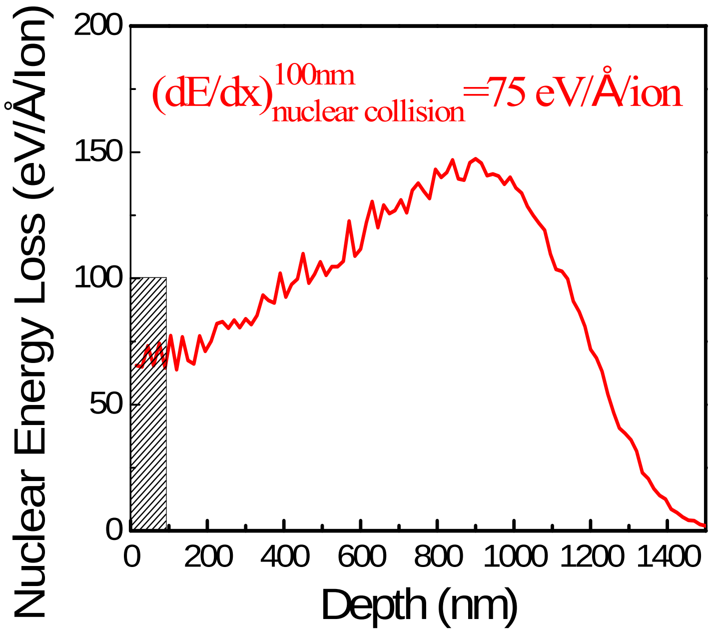
$$k = \frac{< D_{mix} t >}{\Phi F_D} = (\frac{< Dt >}{\Phi F_D})_{coll} + (\frac{< Dt >}{\Phi F_D})_{thermalspike}$$

Binary collision theory:

$$\frac{< Dt >}{\Phi F_D}_{coll} = 1\sim7 \text{ Å}^5/\text{eV}.$$

$D_{mix}$: intermixing coefficient, ~1.4 Å$^2$/s
t: irradiation time, 16200 s
$\Phi$: ion fluence, 10 ions/Å$^2$
$F_D$: deposited ion energy, 75 eV/Å/ion

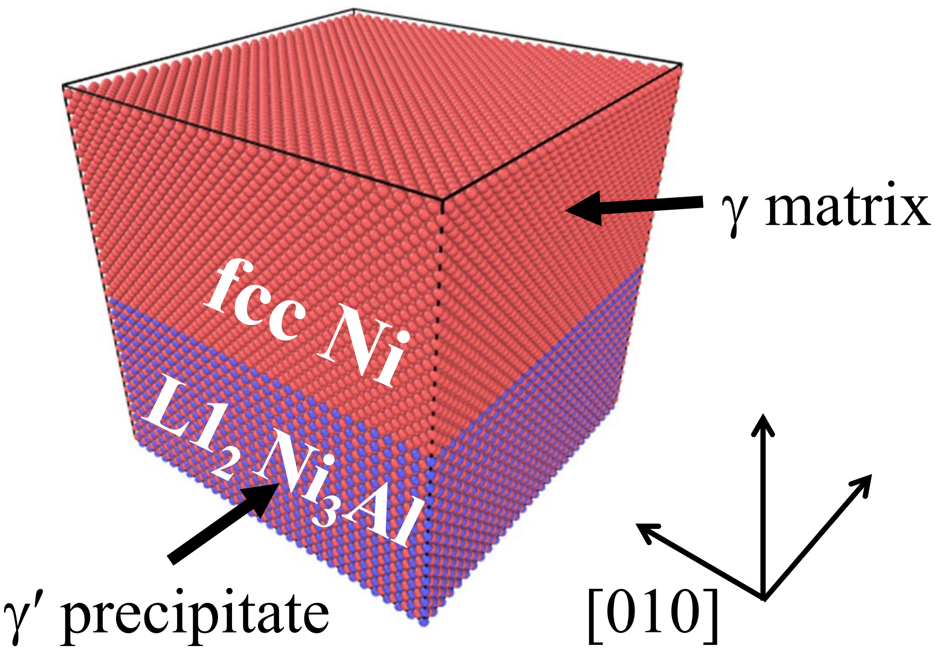
*k* is estimated to be ~ 30 Å$^5$/eV.

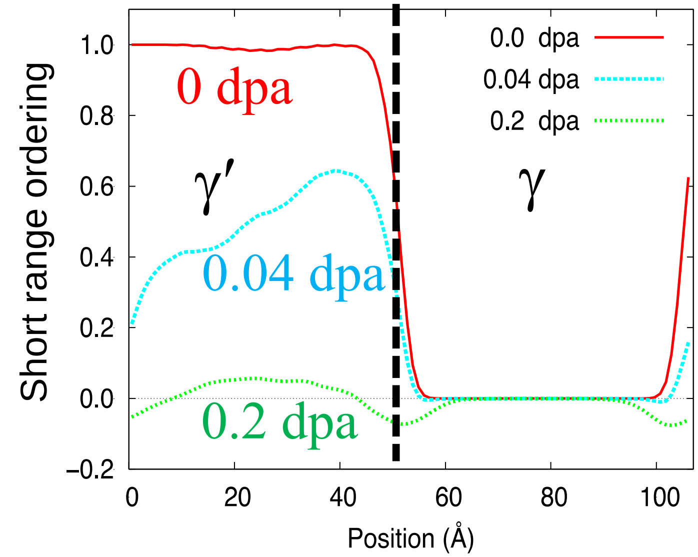


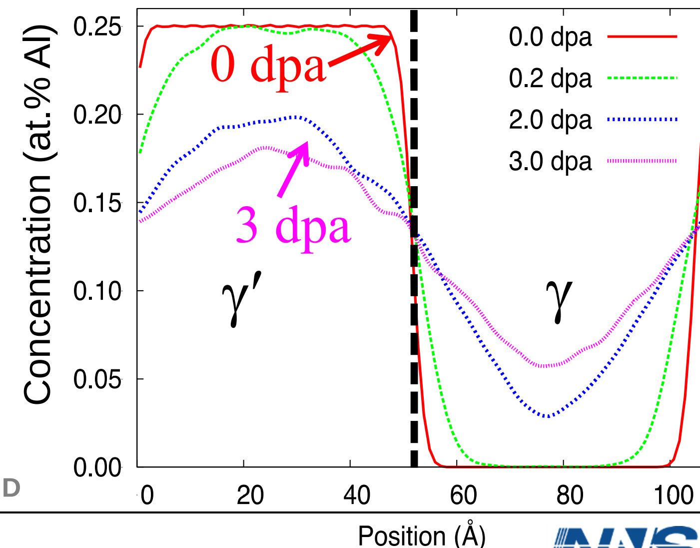

- **Thermal spike is the major mixing mechanism.**

# Atomic modeling

*M.J. Demkowicz and T. Lee*

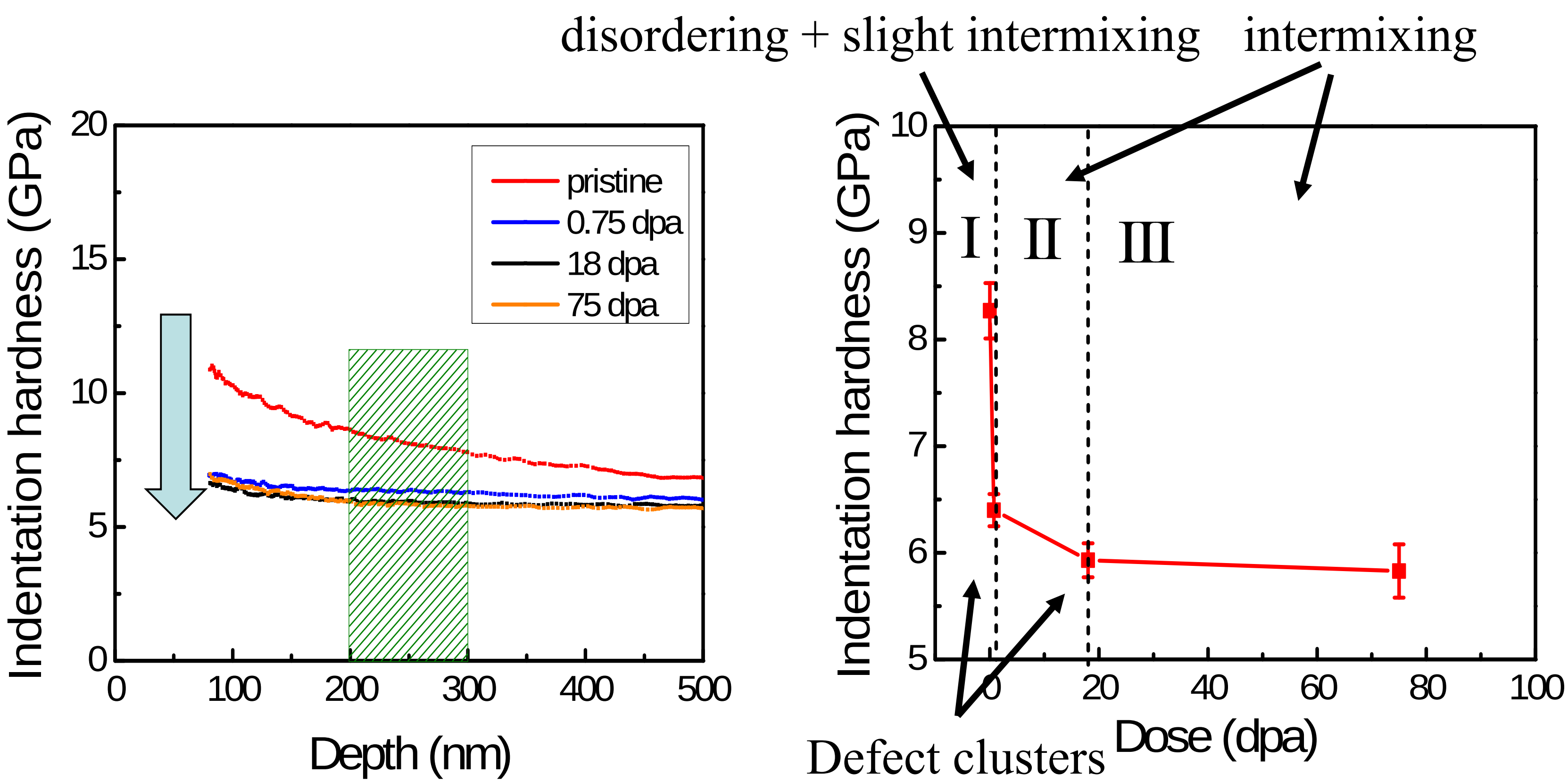


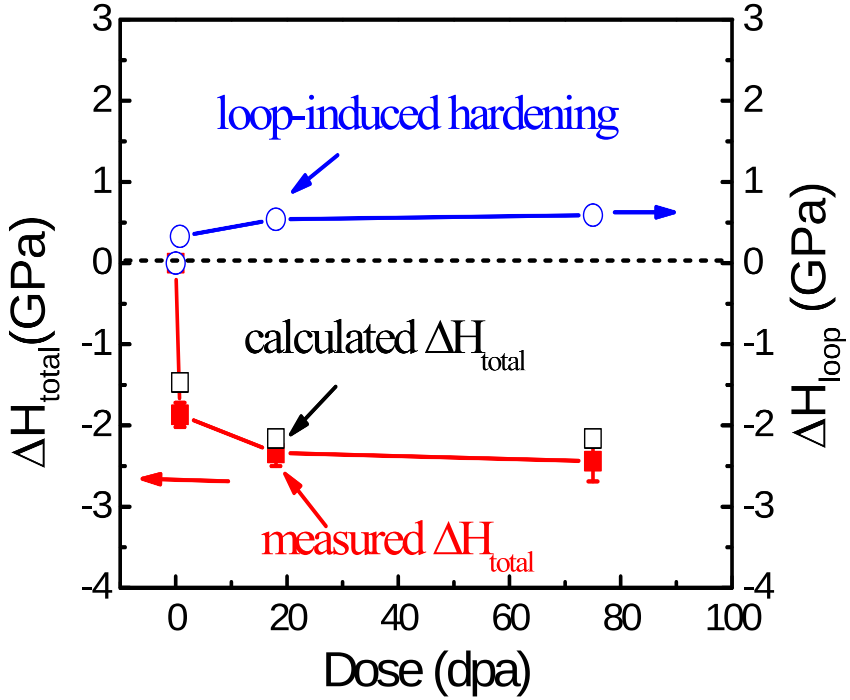

- **γ' precipitates at RT dissolves much more slowly than it disorders.**
- **Mixing efficiency ( $k$ ) is ~ 20 Å$^5$/eV**

# Nanoindentation hardness




- **Intermixing does not influence hardness at high doses (>18 dpa).**

# Nanoindentation hardness




$$\Delta\tau_{cT} = \tau_{cL} - \tau_{cO} - \tau_{c\varepsilon}$$

- **Disordering-induced softening:**

$$\tau_{cO} = \frac{\gamma_{APB}}{2b}\left[\left(\frac{3\pi^2\gamma_{APB} fl}{32T}\right)^{1/2} - f\right]$$

$\gamma_{APB}$: anti-phase boundary energy.

$f$ : volume fraction of the precipitates.

$l$ : separation distance of precipitates.

$T$ : line energy of dislocations.

- **Dislocation loop-induced hardening:**

$$\tau_{cL} = \alpha\mu b\sqrt{Nd}$$

N: loop density. d: loop size

b: Burgers vector. μ: shear modulus

- **Intermixing-induced softening:**

$$\tau_{c\varepsilon} = 1.2 f^{1/2}\left(\frac{T^3\mu\varepsilon}{b^3 r^3}\right)^{1/4}$$

$\varepsilon$ : misfit strain $\varepsilon = \Delta a / a$

$r$ : size of precipitates

# Conclusions

- The $\gamma'$ precipitates become fully disordered at a dose of 0.3 dpa.
- The $\gamma'$ precipitates partially dissolve after irradiation up to 75 dpa and the chemical intermixing mainly originates from thermal spike effects.
- Combining effects of defect clusters, disordering and dissolution determine the evolution of hardness.